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DYNAMICS OF PSR J0045-7319/B-STAR BINARY AND NEUTRON STAR FORMATION

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Recent timing observations have revealed the presence of orbital precession due to spin-orbit coupling and rapid orbital decay due to dynamical tidal interaction in the PSR J0045-7319/B-star binary system. They can be used to put concrete constraints on the age, initial spin and velocity of the neutron star.

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Introduction

One of the fundamental questions in the studies of pulsars concerns the physical conditions of neutron star at birth. Of particular interest is the initial spin periods and velocities of pulsars, as they are related to such issues as supernova explosion mechanism and gravitational wave emission from core collapse. The PSR J0045-7319 binary (containing a 0.93 s radio pulsar and a massive B-star companion in an eccentric, 51 days orbit [1]) is unique and important in that it is one of the two binary pulsars discovered so far that have massive main-sequence star companions (The other one is PSR B1259-63). These systems evolve from MS-MS binaries when one of the stars explode in a supernova to form a neutron star. Thus the characteristics of such pulsar binaries can potentially be used to infer the physical conditions of neutron star formation. The PSR J0045-7319 system, in particular, owing to its relatively small orbit and "clean" environment (the mass loss from the B-star is negligible), exhibits interesting dynamical orbital behaviors, which allow for concrete constraints on the initial spin and kick of the pulsar.

Dynamics of PSR J0045-7319/B-star Binary

Spin-Orbit Coupling: Based on earlier timing data, it was suggested that classical spin-orbit coupling is observable in the PSR J0045-7319/B-star binary [2]. This spin-orbit coupling results from the flattening of the B-star due to its rapid rotation: the dimensionless distortion is related to the spin rate Ω_s

by $\varepsilon \sim \Omega_s^2/(GM_c/R_c^3)$, and the resulting quadrupole moment is $Q \sim kM_cR_c^2\varepsilon$, where M_c, R_c are the mass and radius of the B-star, k is a constant measuring the mass concentration inside the star. There are two effects associated with this spin-induced quadrupole moment: (i) The *advance of periastron* due to perturbation in the interaction potential $\Delta V \sim GM_pQ/r^3$ (where M_p is the pulsar mass, r is the separation); (ii) When the B-star's spin $\mathbf{S}$ is misaligned with the orbital angular momentum $\mathbf{L}$, there is an interaction torque $N \sim (GM_pQ/r^3)\sin\theta$ (where θ is the angle between $\mathbf{S}$ and $\mathbf{L}$) between the spin and the orbital motion, giving rise to *precessions of* $\mathbf{S}$ *and* $\mathbf{L}$ around a fixed $\mathbf{J} = \mathbf{L} + \mathbf{S}$. Both of these effects have been confirmed by recent observation[3].

Rapid Orbital Decay: Recent timing data also reveal that the orbit is decaying[3], on a timescale of $P_{\rm orb}/\dot{P}_{\rm orb} = -0.5$ Myr (shorter than the lifetime of the $8.8M_\odot$ B-star and the characteristic age of the pulsar). Since mass loss from the B-star is negligible (as inferred from dispersion measure variation), the orbital decay must have a dynamical origin. It was suggested that dynamical tidal interaction can do job[4]: Each time the pulsar passes close to the B-star, it excites internal oscillations (mainly g-modes) in the star, transferring orbital energy to the stellar oscillations. An interesting prediction of this theory is that in order for the energy transfer to be sufficiently large to explain the observed orbital decay rate, $\mathbf{S}$ and $\mathbf{L}$ must be not only misaligned but also more or less anti-aligned. The reason that *retrograde rotation* can significantly increase the tidal strength is the following: During a periastron passage, the most strongly excited modes are those (i) propagating in the same direction as the orbital motion, (ii) having frequencies in the inertial frame comparable to the "driving frequency" (equal to twice of orbital frequency at periastron), and (iii) coupling strongly to the tidal potential. Since the higher-order (lower frequency) g-modes have smaller couping coefficients than the low-order ones, the trade-off between (ii) and (iii) implies that the dominant modes in energy transfer are those with frequencies higher than the resonant mode. If the B-star were nonrotating, the dominant modes would be g_5-g_9, and the inferred $\dot{P}_{\rm orb}$ would be two orders of magnitude too small to explain the observed value. However, a retrograde rotation "drags" the wave modes backwards and reduces the mode frequencies in the inertial frame. As a result, energy transfer is dominated by lower-order modes, which couple much more strongly to the tidal potential. At $\Omega_s = -0.4(GM/R^3)^{1/2}$ (projected along the $\mathbf{L}$ axis), for example, the dominant modes are g_3-g_5, and the energy transfer increases by two orders of magnitude as compared to the nonrotating value. A recent analysis[5] of the radiative damping of g-modes indicates that an additional ingredient, i.e., differential rotation, is needed to compensate for the longer damping times of lower-order g-modes.

Constraints on the Initial Conditions of PSR J0045-7319

Evidence for Supernova Kick: As mentioned before, the PSR/B-star binary evolves from a MS-MS binary. At this earlier stage, the B-star's spin is most likely to be aligned with the orbital angular momentum. The only way to transform this aligned configuration into the current misaligned configuration is that the supernova was asymmetric and gave the pulsar a kick [2,3], and the kick velocity must have nonzero components (i) in the direction out of the original orbital plane, and (ii) in the direction opposite to and with magnitude larger than the original orbital velocity. Let the total mass, semimajor axis, eccentricity of the system before and after the supernova be (M_i, a_i, 0) and (M_f, a_f, e_f). The kick velocity is given by

$$|V| = (GM_f/a_f)^{1/2}\left[2\xi - 1 + \xi\eta^{-1} - 2(1-e_f^2)^{1/2}\xi^{3/2}\eta^{-1/2}\cos\theta\right], \qquad (1)$$

where $\eta = M_f/M_i < 1$ and $\xi = a_f/a_i$. With $(1+e_f)^{-1} \leq \xi \leq (1-e_f)^{-1}$ and $125^o \leq \theta \leq 155^o$ (as constrained by the measurement of precessions [3] and for retrogarde rotation; tighter constraint can be obtained using the observed surface velocity of the B-star, but it depends on the precession phase), we get $|V| \gtrsim (GM_f/a_f)^{1/2} \simeq 125\ \mathrm{km\,s^{-1}}$, where we have used the current observed values for a_f and e_f. Orbital evolution since the supernova tends to make a_f and e_f larger, hence decreases this lower limit.

Age of the Binary and Initial Spin of the Pulsar: The theory of dynamical-tide induced orbital decay gives a scaling relation [4]

$$\dot{P}_{\rm orb} \propto P_{\rm orb}^{-7/3-4\nu}(1-e)^{-6(1+\nu)}, \qquad (2)$$

and a similar relation for $\dot{e}$, where ν lies in the range $0.2 - 1.0$, reflecting the uncertainty in the rotation rate. The proportional constant depends on the (uncertain) mode damping time. Using the observed value of $\dot{P}_{\rm orb}$ for the current system, this constant can be fixed, and the equations can be integrated backward in time. It was found that regardless of the uncertainties, the age of the binary since the supernova is less than 1.4 Myr. This is significantly smaller than the characteristic age (3 Myr) of the pulsar, implying that the latter is not a good age indicator. The most likely explanation for this discrepancy is that the initial spin period of the pulsar is close to its current value. Thus the pulsar was either formed rotating very slowly, or has suffered spin-down due to accretion in the first $\sim 10^4$ years (the Kelvin-Holmholtz time of the B-star) after the supernova (E. van den Heuvel, private communication).

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